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A Review of Membrane Optics Research

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Technical Memorandum

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14. ABSTRACT
This report is a compendium of work on optical quality membranes performed by researchers of the Air Force Research Laboratory, Directed Energy Directorate at Kirtland Air Force Base, New Mexico during the period 1997-2004. It also includes work carried out under contractual agreements between AFRL/DE and its contractors. The intent is to provide in one location what is, to our knowledge, the most complete collection to date of references and published material on membrane mechanics and optics, including theory, finite element modeling, experimental results, coatings, and imaging, for both initially flat (plate-like) and initially curved (shell-like) membranes.

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1.0 OBJECTIVE

The purpose of this effort was to develop optical-quality, large-area membrane optics.

2.0 SCOPE

This work developed membrane optics from basic physics to useful technologies. Key technical activities included theoretical and experimental investigations into membrane physics, the development of new materials and manufacturing processes for the production of optical-quality membranes, and the transition of membrane optics into useful technologies.

3.0 BACKGROUND

This report is a compendium of work on optical quality membranes performed by researchers of the Air Force Research Laboratory, Directed Energy Directorate at Kirtland Air Force Base, New Mexico during the period 1997-2004. It also includes work carried out under contractual agreements between AFRL/DE and its contractors. The intent is to provide in one location what is, to our knowledge, the most complete collection to date of references and published material on membrane mechanics and optics, including theory, finite element modeling, experimental results, coatings, and imaging, for both initially flat (plate-like) and initially curved (shell-like) membranes.

4.0 TECHNICAL ACTIVITIES

The period 1997-2004 is conveniently divided into the years 1997-2000 and 2000-2004. A detailed record of the results of the first period is given in **Paper 1**, which is Chapter 4, Volume 191 in a book series published by the American Institute of Aeronautics and Astronautics (AIAA). Included in this article is an extensive set of references to research of relevance published prior to 2000.

Paper 2 was published in the interim between the two periods (year 2000), and contains the details of work, briefly mentioned in Paper 1 (pp. 181-183), on the use of an axially directed plunger in the central region of a circular membrane to improve the surface figure of the membrane. **Paper 3**, published in the same year, gives an account of rigorous laboratory optical testing performed on an early sample of CP2 membrane material (CP1 and CP2 were developed at NASA Langley Research Center, and are manufactured by SRS Technologies, Inc., Huntsville, AL, under licensing from NASA). It was clear at that time that this material was beginning to approach the thickness uniformity required for optical applications.

The second period, 2000-2004, was marked in the beginning by a movement away from the pressurized lenticular paradigm so prevalent in earlier efforts (see pp. 147-149 of Paper 1 for a discussion of the pressurized lenticular). At that time (*circa* 2000), a major drawback of the lenticular concept was the unavailability of membranes with the extreme thickness uniformity required for optical applications, as mentioned above. As an alternative, research began on the design and feasibility of a near net-shape, stress-coated membrane mirror. This concept has several advantages over the pressurized lenticular, including i) elimination of the need for an optical quality canopy, ii) elimination of the need for pressurization, accompanied by a reduction of stress/strain induced in the membrane, and iii) significant reduction of the stiffness, hence weight requirements, for the support structure as a result of the reduction in membrane stress/strain. A very preliminary discussion of the mechanical effects of thin-film coating stress can be found in Paper 1 (see pp. 139-144 and p. 149). A report on the first attempt to cast a net-shape polymer film is given in **Paper 4**.

During the period 2000-2003 considerable effort was directed toward a better theoretical understanding of the mechanics of stress-coated membranes, with funding support from the

Structural Mechanics program office of the Air Force Office of Scientific Research during FY's 2001, 2002, and 2003. This work was published in a comprehensive two-volume AFRL Technical Report, which is included as **Papers 5 and 6** of the present report. The most important result was the discovery of simple prescriptions for the coating stress required to maintain the shape of a membrane, cast and coated on a parabolic mandrel, upon removal from the mandrel. The required stress prescriptions are given in terms of residual stress in the membrane caused by possible mismatch of the coefficients of thermal expansion (CTE) of membrane and mandrel, thermal stress due to CTE mismatch of membrane and coating, and the coating and membrane thicknesses. In **Paper 7** finite element methods were used to study stress-coated membranes with and without gravity loads, with comparisons being made to the theoretical predictions (see also Paper 6). The two were found to be in excellent agreement. Unfortunately, the ability to meet a target coating stress prescription has been found to be extremely problematic due to the inherently complex nature of coating processes, which typically involve numerous interacting process variables whose effects are often difficult to control and direct. **Paper 8** gives the results of an effort to quantify intrinsic coating stress using both bulge testing and vibration analysis, supported by a finite element model. The coating stress values arrived at by these two experimental methods are in good agreement, although higher than typical values found in the literature. Results on the system identification problem for a membrane mirror, based on its dynamic response to acoustic excitation, are reported in a recent Master's thesis, **Paper 9** of this collection (see **Paper 10** for a related discussion on the connection between membrane dynamics and the use of diffractive wavefront control).

Important progress has been made in the meantime toward the manufacture of uniform thickness membranes by SRS Technologies, Inc., funded in part by the small business innovative research (SBIR) program of AFRL. This work has resulted in the development of a process for

manufacturing the uniform thickness membranes required for optical applications. The world's first optical quality membrane material is referred to as CP1-DE by SRS Technologies, in recognition of the funding and technical support received from the Directed Energy Directorate of AFRL and its researchers. **Paper 11** is a detailed report on the metrology and results that first demonstrated the optical quality of CP1-DE (then referred to simply as CP1). In **Paper 12** several key properties of membrane optical systems are characterized, and their effects on optical aberrations are analyzed. The design and testing of an experimental membrane mirror system using electrostatic forces to tension and figure the membrane is discussed in **Paper 13**.

The availability of optical quality membranes solves the problem mentioned earlier of providing a uniform thickness canopy for a lenticular configuration, leading full circle to a reconsideration of the pressurized lenticular as a viable structure for optical quality membrane mirrors. The idea now, however, would be to use as the reflecting element a near net-shape membrane with a coating whose intrinsic stress is near, but slightly less than, the theoretically prescribed value. The slight flattening that obtains after removing the coated membrane from its mandrel could then be eliminated, in principle, by a very small inflationary pressure, returning it to its desired shape. The subsequent pressure-induced strains are expected to be minimal, so that a high-stiffness, and therefore heavy, supporting structure should not be necessary. In **Paper 14** the first results from a finite element model of such a pressure augmented membrane (PAM) mirror are given and compared with theoretical predictions, again showing very good agreement between the two approaches. This work continues, with the latest results reported in **Paper 15**. A laboratory version of a PAM mirror is specified as the deliverable of a Phase II SBIR in 2005.

5.0 CONCLUSIONS

Optical quality membranes are expected in the near future to play a premier role in optical systems requiring, for example, ultra-lightweight windows, or spectral filters. Recent progress in this direction is reported in **Paper 16**. Two Phase II SBIR tasks are in progress with the express purpose of demonstrating high-energy laser (HEL) multilayer coatings on flat membranes using different coating processes (ion-assisted evaporative deposition, and filtered cathodic arc deposition). Both processes are known to produce high density, low defect, coatings on conventional optical components, but it remains to be seen whether such coating processes can be scaled up and successfully applied to large compliant substrates.

Another potentially important application of optical quality membranes is their use as deformable mirrors for wavefront control. It can be shown that a significant portion of typical wavefront aberrations can be removed simply by deforming the boundary ring supporting the membrane, and applying a uniform pressure. Modeling of several different types of boundary control has been initiated, and the first results are reported in **Paper 17**. One feature of a deformable membrane that may have a significant positive impact on its effectiveness is the extremely small air gap between the membrane reflector and its back plate. This air gap is expected to stiffen the membrane, raising its natural frequencies above typical noise-induced vibration frequencies, as well as providing a damping effect. The AFOSR Structural Mechanics program office has committed support to DE researchers for a theoretical and experimental study of these phenomena during FY05.

In closing, it should be noted that the Technology Readiness Level (TRL) for this technology ranges from 3 to 7, where environmental protection windows are at TRL 7, while the PAM is at TRL 3.

6.0 SBIR CONTRACTS

F29601-03-C-0040: SRS Technologies, Inc., Stress Coating for Large Scale Membrane Mirrors

FA9451-04-C-0140: Surface Optics Corporation, Dual Band Mirror System on Flexible Membrane Mirrors for High Energy Lasers

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